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(Meteorological Office)

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Preliminary report on cumulus investigations, East Hill, June - August, 1956, and on plans for future similar work

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1. Introduction

These investigations were made at the Meteorological Office Radar Unit, East Hill (near Dunstable), by the local staff, in co-operation with members of the Department of Meteorology, Imperial College. The principal aim of the work was the co-ordination of visual and radar observations of developing shower clouds, and hence the elucidation of the processes of rain formation in cumulus. On suitable days the evolution of cumulus clouds was followed quantitatively, using a double-theodolite technique for visual measurements, and radar equipment with wave-lengths of 10 cm (PPI and RHI presentation) and 3 cm (RHI presentation). Co-ordinated observations and soundings were made by aircraft of the M.R.F., and by a light aircraft operated for Imperial College from a base at Kenley.

The observations were made on a number of days during the period 14 June to 10 August, 1956. A considerable amount of data was assembled, whose analysis is now being undertaken at Imperial College. The following paragraphs are a provisional summary of the results of the work, a final analysis of which will be prepared under the joint authorship of Meteorological Office and Imperial College staff.

2. Radar echoes in convective weather, not due to precipitation

Ordinarily a swept gain reduction is operated on the receiver of the 10 cm radar, which diminishes the confusing glare on the display tubes produced by permanent echoes from ground obstructions within 10 miles. When we concentrated attention on cumulus at short ranges we removed the swept gain. Although as a result greater difficulty was experienced in distinguishing and photographing non-permanent echoes, we then observed in greater frequency and intensity a kind of echo which had previously been noticed occasionally on the RHI display, but too faintly and rarely to be clearly related to particular clouds, and which as far as we know has not previously been described by radar meteorologists. We found that these echoes are commonly associated with non-precipitating cumulus. They were detectable only on the 10 cm radar, and although carefully sought were not seen on the 3 cm radar, which has a comparable performance in the detection of precipitation. We call them 'mantle echoes'.

A mantle echo is typically a persistent, diffuse, weak echo seen on the RHI presentation in the form of an inverted U or V. Occasionally the echoes appear in the form of a layer with shallow undulations. From simultaneous theodolite measurements we established that the echo is received from the sides of a cumulus or stratocumulus cumulogenitus cloud where they are intercepted by the radar beam, the lower parts of the echo lying near or a

little above the level of the cloud base, and its top corresponding to the cloud summits. With our equipment such echoes were detectable at ranges up to 15 miles. The echo has a fluctuating character, rather like that of precipitation echoes, and is quite unlike the well-known 'angel' echoes which have been reported by R.F. Jones (M.R.P.741) as occasionally observable in great numbers with clear skies. A kind of angel is also seen, however, which usually is received from levels below that of the cumulus bases, and which seems to be associated with convection from the ground. These echoes are seen as compact 'blips' on the radar screen, and give signals of a somewhat steadier character than mantle or precipitation echoes. Sometimes they do not appear on every successive sweep, although an identifiable echo can often be followed for several minutes. With our radar equipment they are observed at ranges of up to about 20 miles.

We first considered that the mantle echoes might be caused by small concentrations of drizzle-size drops within the cumulus, distributed mainly near the walls of the clouds, partly because on some occasions echoes appeared to develop as the clouds aged. This interpretation was hard to maintain when echoes were found in cumulus only two or three thousand feet thick, and also in patches of even shallower stratocumulus cumulogenitus, and had to be abandoned when mantle echoes were found on one day to be well developed in a cloudless sky. On this day convection was occurring, but was limited by an inversion which lay just below the condensation level of the surface air. We now regard the mantle echoes as refractive effects, associated with abrupt gradients of vapour pressure at the edges of clouds, and at the edges of thermals which penetrate into dry layers but do not necessarily reach their condensation level.

The echoes may originate at cloud surfaces which lie across the radar beam, or parts of the beam may enter the cloud before returning to the radar - we have considered effects which might arise because of the shape of thermal and cloud tower caps, and have devised a tentative theory of the echo production in these terms.

The existence of mantle echoes is a help in measuring cumulus, for given the range of a prominent cloud a single-theodolite measurement can be used to determine the height of cloud base; assuming this to be constant within the range of vision estimates can then be made of the range and summit-levels of cumulus too far to be detected by the radar. Mantle echoes rarely extend above 10,000 ft, perhaps because the number of larger clouds which come within radar range is comparatively small, but possibly also because the vapour pressure differences between cloud and clear air become substantially reduced as the temperature falls, so that refractive effects become weaker.

Interesting observations were made on the behaviour of the angel-type echoes. Often these appeared as enhanced ground echoes, extending up to 1,000 to 2,000 ft above the ground in the form of sloping columns. Such echoes may persist for several hours in particular places. Occasionally small blobs of echo become detached from such columns or appear independently at heights of about 2,000 ft, and can be observed for several minutes, apparently moving with the wind. During this period they may ascend by as much as 1,000 to 1,500 ft, but sometimes, especially before disappearing, they seem to descend. On more than one occasion the blips at the up-wind end of a line of angels were at ground level (or at least at zero elevation on the display), but those at the down-wind end of the line were at about 2,000 ft, and on one occasion a weak precipitation echo was noted just beyond this end of the line. We noticed on a few occasions that several ascending angels were located near or beneath rapidly building congestus clouds, and that they may then be followed to levels near the cloud base, or even above it: once we succeeded in photographing the rise of an angel into the centre of a mantle echo above it. We tentatively associate the angels with refractive effects at strong temperature gradients at the caps of rising thermals, and are developing a

theory to explain the essential difference in character between the signals from these angel echoes and the mantle echoes.

It may be remarked that curved lines of angels, up to about 20 miles long, are sometimes observed lying roughly parallel to the edges of shower echoes, but separated from them by about 2 miles. Such lines are almost certainly associated with the micro-fronts produced by cumulonimbus downdraughts, and with the organised growth of new cumulus at the edges of intense showers. More intensive examination of angels may provide new insight into the role of thermals and micro-fronts in the release and organisation of convection.

3. Droplet spectra in cumulus

For the examination of the progress of coalescence in cumulus further information on the droplet spectra is needed, particularly of the occurrence near the bases of droplets of radius exceeding 20-30μ. These may be present in concentrations (up to several per litre) too small to be conveniently sampled by conventional techniques, but nevertheless significant for rain formation. Qualitative observations from the light aircraft, and previous experience, suggest that even small cumulus sometimes contain appreciable concentrations of drizzle-size drops, and the M.R.F., using impaction on silver paper, found droplets of radius about 50μ in concentrations of several per litre inside cumulus of moderate size, 2-3,000 ft above the base. At present it is difficult to account for the growth of such droplets, and further investigation of their true size and concentration is desirable.

4. The formation of showers; the initial radar echo

In recent years much attention has been given to the height at which radar echoes first appear during the formation of showers. It has been found that a developing echo is usually straddled across or even mainly below the 0° C level, and it has been inferred that the precipitation has formed by the coalescence of droplets rather than by the growth of ice crystals. In general the radar observations have not been carefully co-ordinated with the visual appearance of the shower clouds and the impression has spread that precipitation, and hence the radar echo, forms within the central parts of clouds whose tops extend above the 0° C level, often by many thousand feet.

On the other hand, Ludlam and Saunders (Tellus, in press) demonstrated in Sweden the existence of a critical and well-defined level (the fibrillation level) where evanescent traces of precipitation, capable of causing a brief, faint radar echo, for the first time appear in the decaying towers of cumulus summits; when the summits reach above this level showers develop, and, if the temperature there is below 0° C, the cloud tops become glaciated. The height of the fibrillation level varies substantially from occasion to occasion, and, because its height above the cloud base is proportional to the speed of the updraughts in the cloud, it is supposed to be the level at which the coalescence process, active amongst the droplets as they are lifted from the base of the cloud in growing cumulus towers, first leads to the appearance of significant concentrations of raindrops. In the visual observations from which these features were established, no systematic use was made of radar, partly because in the clear Swedish air traces of precipitation in the tops and below the bases of cumulus could be recognised visually at ranges exceeding 30 miles more readily than with the low-power radar available. It seemed clear, however, that the first traces of echo should in general be faint and transient, and would appear consistently at or near a particular level. On the other hand, because of the rapid glaciation which spreads throughout the cloud tops following the initial formation of precipitation, in later towers of the same cloud precipitation develops more copiously and practically simultaneously over a considerable range of heights near and above the 0° C level. Accordingly, it was supposed that the true initial radar echoes are usually small, feeble and short-lived, and practically impossible to detect except by directing the

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radar towards growing clouds visually recognised as likely to become shower clouds. On the other hand, only these echoes provide information on the process by which precipitation forms, as distinct from the more involved processes by which it develops after it has formed at sub-zero temperatures.

At East Hill we found visual observation of clouds to be much more difficult than in Sweden; whereas there the horizontal visibility was rarely less than 40 miles here it hardly ever exceeded 8 miles, and usually only clouds whose range lay between about 5 and 20 miles could be studied. The radar frequently showed columnar echoes extending down to the ground from cumulus within 10 miles, amongst whose summits no signs of fibrillation could be seen, and beneath whose bases was no visible evidence of a shower. Often it was impossible to see cumulus tops beyond 20 miles, and at this range it was sometimes difficult to decide even whether or not they were glaciated. Consequently the opportunities for co-ordinating visual and radar observations were much more restricted than in clean air masses. Nevertheless we were able to make some interesting comparisons, and several times succeeded in making continuous observations of growing cumulus in which initially there was no detectable echo, but in which an echo formed.

We found, in agreement with our previous experience, that radar echoes developed in clouds whose visible towers exceeded a rather well-defined level. If the towers barely reach this level only weak showers are formed, and the radar echo first appears as a narrow upright streak, half a mile or less in width. The streak is usually displayed with a length of 2,000 ft or more, with a top below the peak height attained by the cloud tower by up to about 2,000 ft. If no succeeding towers intervene both the top and the base of the echo descend; the base descends the more rapidly, at a speed of about 1000 ft/min, comparable with the fall-speed of raindrops. Where succeeding towers reach similar heights the echo column broadens; its top remains at about the same level but its base extends down to the ground within a few minutes.

Visual observations show that when the towers of a growing cumulus reach some 2,000 ft or more above the level associated with shower formation, and when, as is usual in our climate, the temperature there is below 0° C, the development of the shower is accompanied by a glaciation of the cloud tops, which within a few minutes spreads throughout the cloud sideways, and downwards to the 0° C level. At the end of this period large parts of the cloud above this level contain significant concentrations of crystals (> 1/litre), probably of very various sizes, including snowflakes and small soft hail pellets. This rapid transformation was in Sweden observed to occur at minimum cloud temperatures varying between about -4° C and -23° C, and is thought to be due, not primarily to the freezing of cloud droplets containing ice nuclei, but mainly to processes of crystal multiplication which are efficiently begun when precipitation-size solid particles, commonly produced by the freezing of some of the large drops grown by coalescence, appear in the cloud tops. According to this view, the glaciation is not usually the cause of shower formation; rather, both are due to the coalescence process reaching an advanced stage at sub-zero temperatures.

5. The development of shower clouds and shower echoes

Once shower formation has begun large droplets and, if glaciation occurs, also large crystals, become spread throughout the cloud. Succeeding towers which rise through the cloud become infected with these large particles, which then grow into precipitation elements over a range of heights much below the level at which the initial elements were formed. Consequently the radar echo from maturing shower clouds is observed to broaden and intensify throughout its height.

Moreover, the concentrations of crystals which infect freshly-rising towers when they reach above the 0° C level are commonly so great that a large part of their liquid content is quickly frozen. The increase in buoyancy

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produced by the accompanying release of latent heat, together with an increase due to the subsequent settling-out of some of this water as precipitation, provides new energy for cloud growth. In Sweden we observed that there is often a new surge in the growth of cumulus soon after glaciation, during which the summits rise at speeds two or three times greater than previously, from heights of around 15,000 ft to near the tropopause, forming massive anvils. Craddock has reported what is clearly the same phenomenon from Malaya, and we now regard this development as a characteristic second phase in the growth of shower clouds. On the radar display it leads to the appearance of very tall and broad (5-10 miles or more) echoes, whose upper parts, corresponding to the anvils, are often mainly diffuse and rather weak, but which contain stronger columns associated with newly-rising towers. At East Hill we found that the tops of these echoes corresponded very closely (within 1,000 ft) to the highest visible tops.

By directing the 10 cm RHI beam into these large echoes with the aerial stationary, and using an amplitude display as a function of range, we were able to observe the occasional momentary increases of echo intensity which occur when lightning discharges pass through the beam (as described and discussed by Jones, Quart. J.R.Met.Soc., 80, 1954, p.579). These momentary increases are found to be coincident with VHF-receiver crackles and the flashes on Sferic direction-indicators, and their observation is a valuable way of exploring particular clouds for electrical activity. We noticed, for example, that lightning occurred only in second-phase clouds, seemed more characteristic of the diffuse rather than the stronger columnar parts of the echo, and sometimes was confined to regions near the cloud tops.

By reducing the gain of the radar we observed that the most intense parts of the precipitation echo usually remain near or below the level of shower formation. The impressive anvil structures may therefore have only an indirect effect on the intensity of shower rains. We suspect that the formation of large hail cannot proceed in second-phase clouds, because of the abundance of crystals, nor in clouds in which the strongest echoes remain below the 0° C level, because the coalescence process then precipitates most of the cloud water before it becomes supercooled. Probably large hail forms only in young clouds containing strong updraughts, so that the temperature at the level of shower formation is well below 0° C. We attempted to confirm these views by relating our observations to reports of hail made by a network of volunteers. Unfortunately the results are unlikely to be conclusive; the network so far used is too thin, and notable hailstorms were rare, except on one or two occasions which fell on week-ends or public holidays.

We regard the small hail which forms within second-phase clouds as a generator of thunderstorm electricity, and stimulated by the observations mentioned above, have devised a theory to account for the failure of clouds with base-temperatures below 0° C to produce thunderstorms.

6. The relation between cumulus properties and screen-level observations

According to the simple parcel theory of convection, the air within cumulus formed by convection from the ground has the wet-bulb potential temperature of the air near the ground. Although there are large departures from the adiabatic processes assumed in the theory, the wet-bulb potential temperature at the cloud base is still fundamental in the discussion of cumulus behaviour. Since it can in principle be obtained on many occasions from ground observations, measurements at the level of the cloud base were made during our aircraft soundings for a comparison between the actual wet-bulb potential temperature at cumulus base and the value obtained from the field of wet-bulb potential temperature shown by the screen-level observations made at synoptic stations. A preliminary inspection suggests that the values are remarkably close - within 1° C. The synoptic observations can therefore be used, when carefully analysed in conjunction with the temperature fields found on upper-level charts, to examine the

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distribution across the country of some important features of cumulus populations, such as the maximum internal buoyancy and the maximum height of the cloud tops. It is hoped that studies along these lines will lead to techniques for improving the forecasting of these features.

7. Plans for future work

(a) Limitations of existing knowledge

The field work already carried out in Sweden and both before and since at East Hill in our opinion points almost conclusively to the importance of the coalescence process in shower formation, and of processes involving the ice phase in shower development. Both kinds of processes can be modified artificially. Before use can be made of the new theories (e.g., in improving thunderstorm forecasts) and before scientific experiments can be made in modification (e.g., the suppression of severe hail - and thunderstorms), the theories must be refined and strengthened by more quantitative expression.

Gaps and weak points exist in our knowledge of both the physical and the meteorological laws operating within the assemblies of water particles which are called cumulus and cumulonimbus. Ultimately the evolution of a cumulonimbus will be described by specifying the particle spectrum as a function of space co-ordinates and time, and accounting for the changes in terms of the predominating physical and dynamical processes. Further, the properties of cloud populations and the meteorological laws controlling them will be elaborated. The task of drawing up these descriptions is immense, and the limited facilities and, more especially, the limited numbers of workers available lead us to concentrate on a few aspects whose clarification seems likely to promote most quickly our powers of prediction and control. These particular aspects are listed below.

(b) Pressing problems

I. Particle size spectra in cumulus

The extensive data already available on drop-size spectra in cumulus unfortunately are not much help in revealing the laws which control the growth of droplets into raindrops. There are two reasons:

(i) the sampling has so far been restricted to volumes of up to 100 cm^3, whereas the largest droplets which are present in concentrations of $1/10^3$ to 10^4 cm^3 are critically important;

(ii) the spectra obtained have not been related to position in the cloud and the cloud history. Showers form within volumes of the order of 1/100 of the volume of an individual cloud. Spectra representative of the other parts are an important property of the cloud but are not representative of the region involved in shower formation.

The first difficulty can be overcome by modifying sampling techniques, but the second can be satisfactorily solved only by making the samples in clouds whose complete history is followed by ground observers.

The droplet spectra must be related to condensation nucleus spectra, the important features of which can be obtained by existing techniques.

II. Processes of crystal multiplication

According to our views the overwhelming majority of crystals in mature cumulonimbus arise from multiplication processes set up by the freezing of large drops, and not primarily from the action of freezing nuclei in small droplets. Experiments are being planned at Imperial College to examine

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the production of crystalline fragments during the freezing of drops. Apart from such laboratory work systematic sampling of shower clouds for their crystal content is needed; this, like the droplet sampling, is best done in co-ordination with ground observers.

III. Cumulus dynamics

Our present knowledge of the nature of the air motions in cumulus, of the factors which determine their scale and of the way in which they are influenced by the cloud particles (e.g., by the release of latent heat), are very rudimentary. Considerable advance will be needed before we understand what governs the size attained by an individual cloud. Model experiments aimed at improving the theory of convective motions are in progress at Imperial College.

As the theory is improved it should become possible to make use of aircraft measurements of cloud-air properties, such as condensed water concentration and temperature. Undoubtedly, however, a new series of measurements, including information on the history of the explored cloud and the exact position of the aircraft in the cloud, will be needed. Eventually the theory will uncover relations between internal cloud properties and external and perhaps more readily measurable features, such as the clear air sounding, the intensity of ground heating, and so on. The behaviour of individual clouds will never become completely predictable, but we may hope that understanding of and ability to forecast the statistical behaviour of populations of cumulus will be greatly improved. Such understanding will be needed to resolve such questions as

"How many clouds will reach a certain size?"

"What total amount of shower rain will fall?" and

"If some clouds are modified, what is the effect on the remainder of the population?"

It is therefore desirable to begin the study of cumulus populations; information for this study can be obtained by ground observers equipped with such facilities as theodolites, radar, and time-lapse cameras, whose observations are co-ordinated with clear-air soundings by radio-sonde or aircraft and with aerial reconnaissance over a wide area, and examined in conjunction with analyses of conditions on the meso- (see next section) and synoptic-scales.

IV. Efficiency of shower clouds

The efficiency of cumulonimbus as precipitation mechanisms, defined, say, as the ratio between the water reaching the ground and that condensed in the cloud throughout its history, seems to vary considerably. Some clouds only 2 or 3 kilometres thick produce intense showers, while others several kilometres thick fail to form precipitation, or their precipitation evaporates before reaching the ground. A knowledge of the precipitation efficiency and the factors which control it would be useful in forecasting practice, and a comparison with the efficiency of artificially modified clouds is essential for a realistic appraisal of techniques of seeding cumulus to produce rain. As a first step in the quantitative study of shower rain, observations of the amount of rain which falls from individual cumulus and populations of cumulus should be included in the field studies mentioned above. Although useful estimates can be made from detailed radar observations, their evaluation is laborious and the results are very sensitive to variations in the drop-size distribution. Moreover the computed rainfall is that within the beam, which at some distance is well above ground level. The radar evidence would

therefore need to be supplemented by records from raingauges, some preferably autographic but for the rest of a simpler pattern than the conventional gauges, disposed within a radius of about 30 mi of the radar station with an average separation of 2-3 mi. Such a network would require several hundred gauges and the recruitment of voluntary observers. Experience in Sweden shows that this is possible, but of course such a network could be maintained only for rather short periods. The British Rainfall Organisation already has comparable networks in well-populated areas, which would provide a splendid basis for the dense network.

It would be very desirable to include in this network stations observing other meteorological elements, so that on selected occasions meso-scale analyses of the convective weather systems could be made. Much attention is being paid to this kind of analysis in U.S.A. (see, e.g., Res.Pap.39, U.S. Weather Bureau). There special networks have been organised with an average station separation of about 30 miles. Such a network could more easily be established in England, where the separation of stations making synoptic reports is already about this value, or is in some districts even less.

V. Seeding experiments

As the quantitative observation and theory of cumulus progress, it will become possible to plan seedings aimed at modifying their behaviour, and to measure the effect of the seedings by quantitative comparison of the observed and the predicted natural behaviour. All evaluations of seeding experiments are based upon such a comparison, with an accuracy which depends upon the errors in both the observed and predicted behaviour. The accuracy of the former depends only upon the suitability of the observing technique, while that of the latter depends also on the design of the experiment. In the absence of spectacular events, such as the explosion of treated clouds, and in view of the great variability in the natural behaviour, a sound theory must be used to design the details of an experiment, aimed at producing a predictable and detectable effect. For example, in Sweden the recognition and interpretation of the fibrillation level led to the dry-ice seeding of a cumulus whose summits were at all times below the fibrillation level; following the seeding, the cloud produced a shower, so that its behaviour was demonstrably different from that of all other clouds present, some of which were producing showers naturally. This is the first time such a difference has been established. Only by improved and repeated experiments of such a nature can we realise the possibilities of usefully modifying clouds and precipitation.

8. Facilities for future investigations

It seems clear to us that material progress with the difficult problems mentioned above can be made only by field investigations in which very detailed and comprehensive observations are made by the careful co-ordination of ground observers, using visual and radar techniques, and aircraft observers. In the recent work aircraft participated, but did not enter clouds. We are very conscious of the benefits of co-ordinating the visual and radar observations, and would like to continue this work with the added co-operation of aircraft, in order to examine selected clouds by all three techniques.

Unfortunately this is not possible at East Hill owing to restrictions on flying in and near clouds. Since another field site may need to be chosen, we summarise the desirable conditions as follows:

(a) unpolluted air, for clarity of vision and freedom from disturbed nucleus spectra;

(b) good radar and visual horizons;

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(c) freedom from restrictions on flying in cloud;

(d) proximity to radio-sonde station and other meteorological facilities;

(e) frequent occurrence, at least in some season, of well-developed cumuliform clouds.

These conditions are not all easily fulfilled anywhere in the British Isles. It must be borne in mind, however, that field studies of the kind envisaged can accumulate in one favourable month material requiring a year for its digestion. It is therefore suggested that they could be made at a site not permanently occupied, either in Britain or abroad. (It is not unlikely that sufficient progress could then be made to remove the need for flight through clouds in future work, so that it could continue without much hindrance at a more convenient place.) Since the aircraft and the ground observers are readily mobile the main difficulties in establishing a temporary site are providing staff accommodation and radar. The radar should comprise a range-height set and a plan-position set, the latter not necessarily under direct control of the ground observers but equipped with an automatic camera. It might prove possible to solve all problems by finding an RAF base well away from busy airways but not too remote (e.g., in S.W. England), with suitable accommodation, with facilities for communicating to aircraft, with a plan-position radar on the airfield or nearby whose display could be repeated at a meteorological control, and to which a 3-cm height-range radar could be taken for the duration of the field work. While the prospects of such a solution are explored it is recommended that field work should be continued at East Hill, with whatever aircraft co-operation is practicable.